SEMICONDUCTOR DEVICE Having Aluminium Conductors

BACKGROUND OF THE INVENTION

Th~~e~~is invention relates to a semiconductor device and a method for producing the same.

In recent years, due to the miniaturization of semiconductor devices, the width of metal conductor has tend~~s~~ed to become small. Thus, to prevent an aluminum conductor from being broken due to migration and to prevent hillocks from occurring due to ~~the~~ such migration, there has been generally used a method of adding copper of about 0.5% ~~in~~ to the aluminum used for the aluminum conductor. generally employed has been However, the spacing of metal conductor portions as well as the metal conductor width also tends to ~~also~~ become quite small. Thus, if any precipitate containing copper exists between two of the metal conductor portions, it can become~~s~~ ~~the~~ a cause of short fault. To address this problem, it is proposed, in JP-A-8-186175 [and etc], to adopt a method comprising the steps of forming aluminum film at a high temperature so that copper may be dissolved in the aluminum, and quenching the aluminum film so that the copper may be prevented from being precipitated during the cooling thereof.

SUMMARY OF THE INVENTION

The conventional method in which an aluminum conductor containing copper is formed by use of the quenching treatment, is not sufficient when the spacing

between aluminum conductor portions adjacent to each other (hereinafter referred to as "conductor spacing") becomes ~~further~~ so narrow a to ~~be~~ not be more than 0.4 μm.

Thus, the first object of the invention is to provide a semiconductor device having high reliability.

The second object of the invention is to provide a semiconductor device having a high yield.

The third object of the invention is to provide a semiconductor device having such an interconnect structure ~~as~~ that short circuits are unlikely to ~~hardly~~ occur~~s~~.

The precipitation of copper regarding the aluminum conductor is found to proceed due to the diffusion of copper atoms existing in crystal grain boundaries and in crystal grains. Thus, in order to prevent the precipitation from occurring, it is necessary to suppress the diffusion of the copper atoms existing in the aluminum conductor. After performing intensive research~~es~~ for obtaining means for suppressing the diffusion of the copper atoms, the inventors of the present invention have discovered that, by adding ~~in the aluminum conductor~~ an additive to the aluminum conductor, which additive suppresses the diffusion of copper, the precipitation can be prevented.

The subjects of the invention can be solved by a semiconductor device having any one of the following constitutions 1 to 5:

(1) a semiconductor substrate, and an aluminum conductor containing aluminum as the main constituent thereof, which aluminum conductor is provided on the side

of one main face of the substrate, the aluminum conductor being made to contain copper and nickel therein. Further, it is preferred that in some region of the semiconductor device, the conductor spacing is not more than 0.4 μm and that the content of ~~the~~ nickel is not less than 0.02 at.% but not more than 1 at.%;

(2) a semiconductor substrate, an aluminum conductor containing aluminum as the main constituent thereof, which aluminum conductor is provided on the side of one main face of the substrate, and an adjacent film (barrier film) adjacent to the aluminum conductor, which adjacent film contain~~ing~~s titanium and titanium nitride as the main constituents thereof, the aluminum conductor being made to contain copper and nickel therein. Further, it is preferred that, in some region of the semiconductor device, the conductor spacing is not more than 0.4 μm and that the content of the nickel is not less than 0.02 at.% but not more than 1 at.%;

(3) a semiconductor substrate, and an aluminum conductor containing aluminum as the main constituent thereof, which aluminum conductor is provided on the side of one main face of the substrate, the aluminum conductor being made to contain copper and silicon therein. Further, it is preferred that, in some region of the semiconductor device, the conductor spacing is not more than 0.4 μm and that the content of the silicon is not less than 0.05 at.% but not more than 0.4 at.%;

(4) a semiconductor substrate, an aluminum

conductor containing aluminum as the main constituent thereof, which aluminum conductor is provided on the side of one main face of the substrate, and an adjacent film (barrier film) adjacent to the aluminum conductor, which adjacent film contain~~ing~~s titanium and titanium nitride as the main constituents thereof, the aluminum conductor being made to contain copper and silicon therein; and

(5) a semiconductor substrate, an aluminum conductor containing aluminum as the main constituent thereof, which aluminum conductor is provided on the side of one main face of the substrate, and an adjacent film (barrier film) adjacent to the aluminum conductor, which adjacent film contain~~ing~~s one kind selected from the group consisting of ruthenium, platinum and iridium as the main constituent thereof, the aluminum conductor being made to contain copper. Further, it is preferred that nickel not less than 0.02 at.% but not more than 1 at.% is contained in the aluminum conductor and that silicon not ~~not~~ less than 0.05 at.% but not more than 0.4 at.% is contained in the aluminum conductor.

In the specification, the term "main constituent of the metal conductor" means a component contained in the metal conductor, the amount of which component is the largest one of all components in the metal conductor.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 is a sectional view of the main part of a semiconductor device according to the first embodiment of

the invention.

Fig.2 is a graph showing the dependence of the diffusion coefficient of aluminum upon copper content with respect to a low content range of copper.

Fig.3 is a graph showing the dependence of the diffusion coefficient of aluminum upon copper content with respect to a high content range of copper.

Fig.4 is a graph showing the dependence of the precipitation rate of copper upon nickel content with respect to a low content range of nickel.

Fig.5 is a graph showing the dependence of the precipitation rate of copper upon nickel content with respect to a high content range of nickel.

Fig.6 is a graph showing the dependence of the precipitation rate of copper upon silicon content with respect to a low content range of silicon.

Fig.7 is a graph showing the dependence of the precipitation rate of copper upon silicon content with respect to a high content range of silicon.

Fig. 8 is a sectional view of the main part of another semiconductor device according to the second embodiment of the invention.

Fig. 9 is a graph showing the dependence of copper precipitation rate upon the kind of materials used for a barrier film in a case where an aluminum film containing copper and nickel is in contact with the barrier film.

Fig. 10 is a graph showing the dependence of

copper precipitation rate upon the kind of materials used for the barrier film in a case where an aluminum film containing copper and silicon is in contact with the barrier film.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE INVENITON

The embodiments of the invention are explained in detail below ~~while~~ with refer~~ring~~ence to the drawings.

First, the sectional structure of the main part of a semiconductor device according to the first embodiment of the invention is shown in Fig. 1. In the semiconductor device according to the first embodiment, as shown in Fig. 1, diffusion layers 2, 3, 4 and 5 are formed on a silicon substrate 1. On which layers are ~~formed~~ is gate dielectrics 6 and 7 and gate electrodes 8 and 9 are formed on the layers 2 through 5, so that MOS transistors are formed. Each of the gate dielectrics 6 and 7 is, for example, made of silicon oxide film or silicon nitride film, and each of the gate electrodes 8 and 9 is, for example, made of polycrystalline silicon film or metal thin film or metal silicide film or a layered structure of these films. The MOS transistors are separated by an isolation film 10 of, for example, silicon oxide film. On the upper portion and side wall of the gate electrodes 8 and 9, there are formed insulating films 11 and 12 which are made of, for example, silicon oxide film. On the whole, an insulating film 13 is formed on upper faces of the MOS transistors ~~is formed an~~ This is insulating film 13 is

made of, for example, BPSG (Boron-Doped Phospho Silicate Glass) film, or SOG (Spin On Glass) film, or silicon oxide or silicon nitride film formed by a chemical vapor deposition method or a sputtering method. In contact holes formed in the insulating film 13, there are formed plugs, each comprising a main conductive film 15 coated with adjacent conductive film 14a, 14b (first conductive film) for preventing diffusion, each of which plugs is connected to each of the diffusion layers 2, 3, 4 and 5. To the plugs is connected ~~the~~ a first layered interconnection comprising a main conductive film 17 coated with adjacent conductive films 16a and 16b for preventing diffusion. The layered interconnection is, for example, provided by the steps of forming the main conductive film 17 by use of a sputtering process after having formed the adjacent conductive film 16a by the sputtering process, forming thereon the adjacent conductive film 16b by the sputtering process, and forming an interconnect pattern by the etching thereof. If precipitates containing copper remain during the etching without being removed, a short ~~will~~ is likely to ~~occurs~~ occur in a case where the conductor spacing 28 is narrow. On the first layered interconnection, plugs, each comprising a main conductive film 20 coated with an adjacent conductive film 19, are formed in contact holes formed in insulating film 21. To these plugs is connected the second layered interconnection which comprises a main conductive film 23 coated with adjacent conductive films

22a and 22b. The second layered interconnection is, for example, provided by the steps of forming the main conductive film 23 by sputtering after having formed the adjacent conductive film 22a by sputtering, forming thereon the adjacent conductive film 22b by sputtering, and forming an interconnect pattern by the etching thereof.

The materials of the main conductive film 17 and the main conductive film 23 respectively provided in the first and second layered interconnections are, for example, aluminum, in which copper, is added to provide good migration resistance. In the p embodiment, in order for shorts not to occur due to the precipitation of copper, even in the case where the conductor spacings 28 and 29 are not more than 0.4 μm, at least one ~~kind~~ material selected from the group consisting of nickel and silicon is added to each of the main conductive film 17 and the main conductive film 23. As a ~~the~~ method for ~~of the~~ adding those materials, ~~there is used,~~ for example, sputtering using a target of an alloy or multi-sputtering using a plurality of targets can be used. As regards the contents of copper, nickel and silicon, they are explained below in connection with the effect brought about in the embodiments of the invention.

For explaining in detail the effect brought about in the embodiments, there are shown analysis examples by use of molecular dynamics simulation. The molecular dynamics simulation is, as disclosed, for example, in Journal of Applied Physics Vol. 54, pages

4864 to 4878, issued in 1983, a method in which force acting on each of atoms is calculated through potential among the atoms and in which, by solving Newton's Equation of Motion, the location of each atom at each time is calculated.

In ~~the~~ this embodiment, by calculating the interaction among different elements by introducing the transfer of electric charge in the above-explained molecular dynamics, the relations explained below can be obtained.

The main effect of ~~the~~ this embodiment is to make it possible to prevent the precipitation of copper by adding nickel and/or silicon, and the respect noting that the fact that the adding of copper is effective for preventing ~~the~~ migration had been already known. However, in order to restrict the content of copper ~~into~~ to a proper value, the dependence of the migration-preventing effect upon the copper content is disclosed at first. The "migration" is a phenomenon that aluminum atoms are diffused due to the influences of heat, stress and electric current with the result that voids and/or hillocks are caused, and The larger the diffusion coefficient is, the more ~~the~~ likely migration ~~becomes~~ ~~apt~~ is to occur. Thus, the migration-preventing effect can be shown by the rate of decrease in the diffusion coefficient. As regards the method for calculating the diffusion coefficient by use of the molecular dynamics simulation, ~~it~~ this is disclosed in Physical Review B Vol. 29 (issued in 1984), pages 5363 to 5371.

In Figs. 2 and 3 ~~are~~ disclose~~d~~ the results of analyzing the dependence of the gain boundary diffusion coefficient D_{GB} of aluminum atoms, existing in the grain boundaries of the aluminum crystalline structure, upon the content of copper, and the dependence of the intra-grain diffusion coefficient D_{IN} of aluminum atoms existing in the interior of aluminum crystalline upon the content of copper. In Figs. 2 and 3, the results are shown while marking with D_{GB0} and D_{IN0} the grain boundary diffusion coefficient and the intra-grain diffusion coefficient, both in the case of no copper being added, respectively. As is apparent from Fig. 2, the diffusion-suppressing effect becomes remarkable when the copper content becomes not less than 0.01 at.%, and this effect becomes saturated when the copper content is 0.02 at.%. Further, as is apparent from Fig.3, the diffusion-suppressing effect becomes lowered when the copper content exceeds 2 at.%. ~~which~~ This occurs because, if the additives are excessively added, the crystal structure of aluminum, which is the main constituent, is disturbed with the result that the diffusion becomes active. Thus, in order to enhance the migration resistance, the copper content is preferred to be not less than 0.02 at.% but not more than 2 at.%. These are the results of the analysis at 700°K at which copper is in a solid solution state in the aluminum crystalline structure. In the case of 500°K, although the precipitation of copper is observed, the Cu-adding effect can be shown similarly even in this case. Further, even

at other temperatures, similar effects can be also shown.

Next, the effect of preventing copper from being precipitated in a case of adding nickel is explained below. In order to do this, There was performed a simulation was performed in which copper was precipitated while setting the temperature at 500°K. ~~and~~ The results of analyzing the dependence of the precipitation rate V upon nickel content are shown in Figs. 4 and 5. In Figs. 4 and 5, the precipitation rate in a case where no nickel was added is marked as "V_0". The precipitation rate in the simulation means such a rate as, at portions in the aluminum crystalline structure where copper atoms gathered, other copper atoms further gather, and is defined as the number of copper atoms gathering ~~per~~ for a unit period of time. As shown in Fig. 4, when the nickel content becomes not less than 0.008 at.%, the effect of preventing the precipitation of copper becomes remarkable. ~~and~~ The effect becomes substantially saturated when the nickel content is 0.02 at.%. Further, as apparent in Fig. 5, when the nickel content exceeds 1 at.%, the effect of preventing the precipitation of copper becomes small. Thus, in order to prevent the precipitation of copper, it is preferred that the nickel content is not less than 0.02 at.% but not more than 1 at.%.

~~Then~~ Next, the effect of preventing copper from being precipitated in a case of adding silicon is explained below. There was performed ~~a~~ A simulation was performed in which copper was precipitated while setting the

temperature at 500°K~~, and the~~. The results of analyzing the dependence of the precipitation rate V upon silicon content are shown in Figs. 6 and 7. In Figs. 6 and 7, the precipitation rate in a case where no silicon was added is marked as "V_0". As shown in Fig. 6, when the silicon content becomes not less than 0.02 at.%, the effect of preventing the precipitation of copper becomes remarkable~~, and the~~. The effect becomes substantially saturated when the silicon content is 0.05 at.%. Further, as is apparent in Fig. 7, when the silicon content exceeds 0.4 at.%, the effect of preventing the precipitation of copper becomes small. Thus, in order to prevent the precipitation of copper, it is preferred that the silicon content is not less than 0.05 at.% but not more than 0.4 at.%.

Incidentally, in prior ~~arts,~~ art arrangements, in order to prevent an aluminum conductor from absorbing silicon atoms from the silicon substrate and/or the silicon oxide film, it had been known to add silicon of about 1 at.% ~~in~~ to the aluminum conductor. However, it is impossible to prevent the precipitation of copper insofar as this amount of the conventionally added silicon is concerned.

In the case of a temperature other than 500°K, the effects of nickel and silicon can also be shown insofar as the temperature is such that ~~one as~~ the copper can be precipitated. At a temperature of not more than 350°K, the rate of precipitation of copper became very slow ~~in rate~~ so that it was impossible to confirm the precipitation of

copper in the simulation. Further, in another case where the temperature becomes such a high temperature as to be not less than 550°K, ~~the~~ copper is apt to be dissolved, so that the precipitation thereof hardly occurs. In the range between 350°K and 550°K, the precipitation of copper is most apt to occur. Thus, in order to prevent the precipitation of copper, it is ~~more~~ prefe~~rred~~able to combine ~~that~~ ~~both~~ ~~of~~ the method of adding nickel and/or silicon and the method of quenching down to a temperature not more than 350°K after forming a film at another temperature not less than 550°K ~~are combined~~. In the specification, the term "quenching" means a cooling performed at a rate larger than the rate of natural cooling occurring by leaving a sample as it is. In order to perform the quenching, there are used, for example, gases or fluids for cooling. Further, in order to realize, prior to ~~the~~ quenching, a state in which copper is sufficiently dissolved, it is preferred to perform the quenching after keeping a high temperature for a period of time of, for example, not less than 5 seconds, following the completion of the deposition of the atoms. In a case where a heat treatment is performed before forming an interconnection pattern by etching etc., after the quenching, it is preferred to perform the heat treatment at such a high temperature as to be not less than 550°K and to perform the quenching when cooling.

In comparing Fig. 4 with Fig. 6, it is found that nickel is more effective than silicon regarding the

precipitation-preventing effect. Further, it becomes possible to make the aluminum conductor lower in resistance in the case of adding nickel than in the case of adding silicon. On the other hand, the addition of silicon has such an effect as to prevent the aluminum conductor from absorbing silicon atoms from the silicon substrate and/or the silicon oxide film.

Next, regarding another semiconductor device relating to the second embodiment of the invention, the sectional structure of the main parts thereof is shown in Fig. 8. The difference between the second embodiment and the first embodiment resides in the respect that, in the first and second layered interconnections, ~~still~~ other barrier films 26a and 26b; 27a and 27b are formed outside of the barrier films 16a and 16b; 22a and 22b of the main conductive films 17 and 23, respectively. Alternatively, although not shown in the drawings, other barrier films of at least one layer may be formed at the outside of the outermost films. Further, the numbers of the layers of the barrier films regarding each of the main conductive films 17 and 23 may be different from each other. In addition, the number of each of the upper and lower layers of the barrier films each provided regarding the main conductive films 17 and 23 may be different from each other. In the case where each of the main conductive films 17 and 23 is made of an aluminum alloy containing copper as an additive, the ~~respect~~ feature that nickel and/or silicon is preferably added therein to prevent the

precipitation of copper is the same as in the first embodiment. ¶ In order to ~~further~~ make the copper precipitation even less likely to ~~hardly~~ occur, it is preferred that the main constituent of each of the barrier films 16a, 16b, 22a and 22b is ~~one kind~~ a material selected from the group consisting of ruthenium, platinum and iridium. The effect brought about by using as a barrier film such material the one kind selected from the group consisting of ruthenium, platinum and iridium as a barrier film is explained below. In Figs. 9 and 10 are shown the results of analyzing the precipitation rate of copper in a case of making the barrier film ~~in~~ come into contact with the aluminum film. In Fig. 9, the results are shown in a case where the copper and nickel contents are 0.5 at.% and 0.1 at.%, respectively. In Fig. 10, the results are shown in another case where the copper and silicon contents are 0.5 at.% and 0.1 at.%, respectively. In Figs. 9 and 10, the precipitation rate in the case of using titanium nitride as a usually used barrier film is set to be V_{TiN}. From Figs. 9 and 10, it is apparent that, in the case where the one kind material selected from the group consisting of ruthenium, platinum and iridium is used as the material of the barrier film, the precipitation of copper is more suppressed in comparison with the case of using titanium nitride as the barrier film. When using the one kind material selected from the group consisting of ruthenium, platinum and iridium as the barrier films 16a, 16b, 22a and 22b, it is preferred to use, for improving the adhesion thereof to the insulating films 13, 21 and

25, ~~the~~ films of titanium nitride or titanium, or ~~the~~ layered film thereof ~~regarding~~ as the barrier films 26a, 26b, 27a and 27b. As regards the main conductive film of the plugs, aluminum in which copper and nickel are added or in which copper and silicon are added may be used, or another material such as, for example, tungsten or silicon may be used. Further, without using the copper-and-nickel-added aluminum or the copper-and-silicon-added aluminum regarding the whole of the film for forming the interconnection, a part of the whole film may be formed by use of one of these Al alloys.

According to the invention, it becomes possible to provide a semiconductor device having high reliability, to provide a semiconductor device having high yield, and to provide a semiconductor device having such an interconnection structure $\boxed{\text{as}}$ that short are highly unlikely to ~~hardly~~ occur~~s~~.